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A NOVEL SCHEME FOR XGM WAVELENGTH CONVERSION BASED ON SINGLE-PORT-COUPLED SOA*

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A novel scheme is proposed for wavelength conversion based on cross-gain modulation (XGM) in a single-port-coupled semiconductor optical amplifier (SOA), in which the input and output share one port. Experimental results and theoretical analysis show that this scheme can be achieved with simple implementation, high output extinction ratio and large input dynamic range. Based on this novel scheme, 2.5 Gbit/s wavelength up conversion with a 12.8 nm span has been demonstrated with the output extinction ratio as high as 15 dB.

Keywords: semiconductor optical amplifier, wavelength conversion, extinction ratio
PACC: 4265K, 4265G, 4255P

I. INTRODUCTION

Wavelength conversion based on cross-gain modulation (XGM) in a semiconductor optical amplifier (SOA) has been studied widely in recent years and it can be achieved with simple implementation, large wavelength conversion span, high conversion efficiency etc.[1] Recently, 100 Gbit/s wavelength conversion using grating assisted cross-gain modulation in a 2 mm long SOA has been reported by Ellis *et al.*[2] But the SOAs exploited in the wavelength converters reported[1−3] are all based on a double-port-coupled structure, which is very difficult to fabricate. In order to suppress the facet reflection, some key technologies,[4] such as extremely low facet reflectivity up to the order of 10^{-6} or tilted active region, aspheric lens and isolator, should be utilized. Moreover, an SOA with a long active region had better be used in XGM wavelength conversion in order to achieve high output extinction ratio and high conversion bit rates;[1,2] thus fabrication of the SOA will be more difficult. Furthermore, as we know, a serious extinction ratio degradation exists in XGM wavelength up conversion based on the conventional scheme.[1] In this paper, a novel scheme is proposed for XGM wavelength conversion based on the single-port-coupled SOA, in which the input and the output share one port. Based on the novel scheme, experimental results show that the output extinction ratio can be higher than 15 dB even in the wavelength up conversion with a 12.8 nm span. A description for the experimental set-up is presented in section Ⅱ, and the conversion results, theoretical model and mechanism for performance improvement are discussed in section Ⅲ.

Ⅱ. EXPERIMENTAL SET-UP

The experimental set-up for the novel wavelength conversion scheme is depicted in Fig.1. The pump DFB laser is derived from the transmitter of 2.5 Gbit/s Error and Jitter Test Set of Aritsu Ltd., and its modulation format can be tunable. The CW probe optical signal and the pump signal are multiplexed by a wavelength division multiplexing (WDM) element, then the multiplexed optical signal is coupled into the SOA via port 1 and port 2 of the circulator. The polarization controller (PC) is set before the SOA to control the polarization states. The frontal facet of the SOA is coated with 10^{-4} order AR film, and the rear facet is coated with 10^{-1} order AR film. The reflected optical signal from the rear facet of the SOA can be selected out from port 3 of the circulator. The 1 nm tunable bandpass filter is used to select out the converted signal from the mixed signals. The variable attentuator following is used to control the received signal power.

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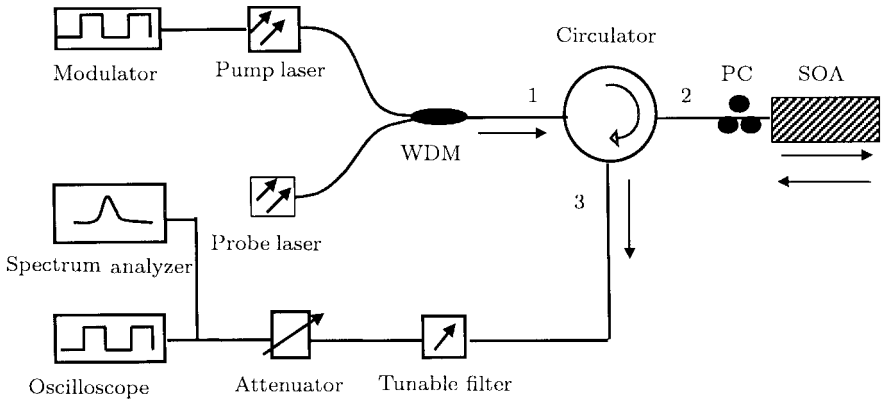


Fig.1. Experimental set-up for the novel scheme based on a single-port-coupled SOA.

The wafer of the SOA, which is fabricated with metal–oxide chemical vapour deposition (MOCVD) epitaxy equipment, consists of the matched quantum wells and tensile-strained quantum barriers based on quaternary material $In_{1-x}Ga_xAs_{1-y}P_y$. The length, width and height of the active cavity are 500, 2.0 and 0.09 μm, respectively. Compared with those conventional schemes,[1−3] the novel scheme can be implemented more simply because the complex fabrication of the long SOA can be avoided.

Ⅲ. RESULTS AND DISCUSSION

A. Experimental results

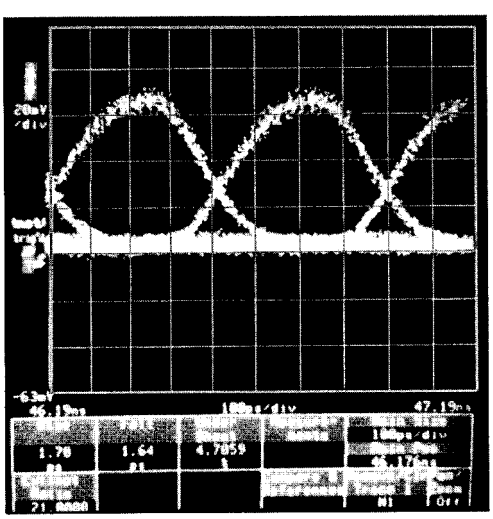


Fig.2. Photograph for conversion results based on the novel scheme with the modulated signal as a 7/8 bit sequence.

The conversion result for the novel wavelength conversion scheme is shown in Fig.2. Corresponding to this conversion result, the modulated signal of the pump laser is a 7/8 bit sequence, and the pump and probe wavelengths are 1549.8 and 1562.6 nm, respectively. The averaged pump power coupled into the SOA is about −1.2 dBm in considering that the coupled efficiency between the SOA chip and the tapered fiber is −3 dB, and the probe power is about −13 dBm. Taking into account the measuring error of the digital oscilloscope, the extinction ratio can be higher than 15 dB by calculating the amplitude ratio of mark and space. It can be concluded that the novel scheme can be achieved with good extinction ratio performance.

B. Theoretical analysis[5,6]

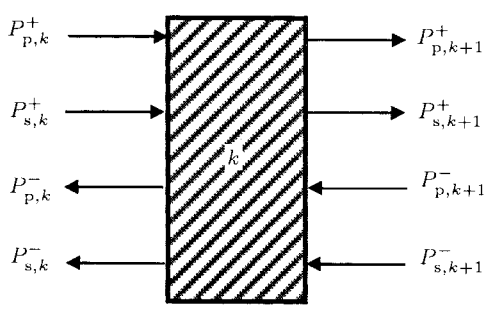


Fig.3. The kth section of the single-port-coupled SOA based on a segmented model.

The theoretical calculation for the novel wavelength conversion scheme is also based on the segmented SOA model. As shown in Fig.3, the SOA is divided into M sections, each of length $\Delta z = L/M$; $P^+_{p,k}, P^+_{s,k}, P^-_{p,k}, P^-_{s,k}$ represent the signal powers under different conditions, where "+" means the forward input signal ,"−" means the reflected signal, "p" corresponds to the pump channel and "s" the probe channel.

For the kth section, the following equations can be derived from the carrier rate equation and travel-

ling equations of the SOA:

$$\frac{\mathrm{d}N_k}{\mathrm{d}t} = \frac{I}{eV} - R(N_k) - \frac{\Gamma g_\mathrm{p}}{A\hbar\omega_\mathrm{p}}(P^+_{\mathrm{p},k} + P^-_{\mathrm{p},k+1}) - \frac{\Gamma g_\mathrm{s}}{A\hbar\omega_\mathrm{s}}(P^+_{\mathrm{s},k} + P^-_{\mathrm{s},k+1}), \quad (1)$$

$$P^+_{\mathrm{p},k+1} = \exp(\Gamma g_\mathrm{p} - \alpha_\mathrm{int})P^+_{\mathrm{p},k}, \quad (2)$$

$$P^+_{\mathrm{s},k+1} = \exp(\Gamma g_\mathrm{s} - \alpha_\mathrm{int})P^+_{\mathrm{s},k}, \quad (3)$$

$$P^-_{\mathrm{p},k} = \exp(\Gamma g_\mathrm{p} - \alpha_\mathrm{int})P^-_{\mathrm{p},k+1}, \quad (4)$$

$$P^-_{\mathrm{s},k} = \exp(\Gamma g_\mathrm{s} - \alpha_\mathrm{int})P^-_{\mathrm{s},k+1}, \quad (5)$$

where N_k is the carrier density of the kth section, I is the injection current, V is the volume of the active region, $g_{\mathrm{p(s)}}$ is the gain coefficient, $\hbar\omega_\mathrm{p}$ is the photon energy, Γ is the mode confinement factor and α_int is the internal loss coefficient. When the non-radiative recombination, Auger recombination and recombination with defects are all included, the recombination rate $R(N_k)$ should be expressed as

$$R(N_k) = A_\mathrm{nr}N_k + BN_k^2 + CN_k^3, \quad (6)$$

where the three terms represent recombination with defects or surface, spontaneous emission and Auger recombination, respectively.

As we know, gain dispersion should be also considered in analysing the output extinction ratio performance, and the gain coefficient can be derived from the following model:

$$g_i^k = g_{\mathrm{A}i}(N_k - N_0) - r_2(\lambda_i - \lambda_N)^2 + r_3(\lambda_i - \lambda_N)^3, \quad (7)$$

where N_0 is the transparent carrier density, λ_i is the signal wavelength, $g_{\mathrm{A}i}$ is the differential gain coefficient, r_2 is the coefficient related to the gain bandwidth of the SOA, and r_3 is the coefficient related to the asymmetry of the gain spectrum. λ_N is the gain peak wavelength corresponding to a certain carrier density and can be expressed as

$$\lambda_N = \lambda_\mathrm{p} - k_0(N_k - N_0), \quad (8)$$

where λ_p is the gain peak wavelength corresponding to the transparent carrier density and k_0 is the gain shift coefficient.

The boundary conditions for the single-port-coupled SOA can be derived from the following equations:

$$P^+_{\mathrm{p},1} = T_1P^\mathrm{in}_\mathrm{p}, \quad P^-_{\mathrm{p},M+1} = R_2P^+_{\mathrm{p},M+1}, \quad P^\mathrm{out}_\mathrm{p} = T_1P^-_{\mathrm{p},1},$$
$$P^+_{\mathrm{s},1} = T_1P^\mathrm{in}_\mathrm{s}, \quad P^-_{\mathrm{s},M+1} = R_2P^+_{\mathrm{s},M+1}, , \quad P^\mathrm{out}_\mathrm{s} = T_1P^-_{\mathrm{s},1},$$

where T_1 is the facet transmission of the input/output facet and R_2 is the facet reflectivity of the reflected facet. Exploiting Eqs.(1)–(8) and the boundary conditions, the output powers for the pump channel and the probe channel can be determined, then the performance of the novel scheme can be analysed.

As we know, the output extinction ratio is determined by the gain difference of the probe signal after passing through the SOA. The theoretical calculation results for gain difference versus the probe power for different schemes are shown in Fig.4: curve 1 represents the conventional scheme based on a 500 μm long, double-port-coupled SOA; curve 2 represents the same scheme based on a 1000 μm long, double-port-coupled SOA; and curve 3 represents the novel scheme based on a 500 μm long, single-port-coupled SOA. Gain differences versus the averaged pump power for different schemes are shown in Fig.5, in which curves 1, 2 and 3 have the same representations with those in Fig.4. It should be noted that the three SOAs are grown on the same wafer, the injection carrier densities are kept consistent in the calculations for different schemes, and the input extinction ratio is 13 dB. In the theoretical calculation, the pump and the probe wavelengths are 1550 and 1560 nm, respectively. The gain peak wavelength at transparency is 1550 nm, and other coefficients are identical with those in Refs.[6] and [7]. From Figs.4 and 5, it can be shown that the gain difference decreases with increasing probe power while it increases with increasing averaged pump power. However, in the novel scheme, the gain difference is always larger than those in the other two schemes.

Actually, in the novel scheme, the double-pass gain for the probe signal can be achieved, so its gain difference is larger than that in the conventional scheme based on an SOA with an identical length. In addition, the gain difference would not decrease in spite of the existence of transmitting loss in the rear facet of the SOA, because the transmitting loss is identical with that when it is space. Furthermore, the gain saturation in returning pass, due to amplification of the probe signal, would not be too serious just because of the transmitting loss. Whereas, in the conventional scheme based on the 1000 μm long SOA, the gain saturation due to amplification of the probe signal will be serious, especially in the latter semi-section of the SOA. So its gain difference is also smaller than that in the novel scheme. Therefore, the gain difference, as well as the output extinction ratio, in the novel scheme is the largest among the three schemes.

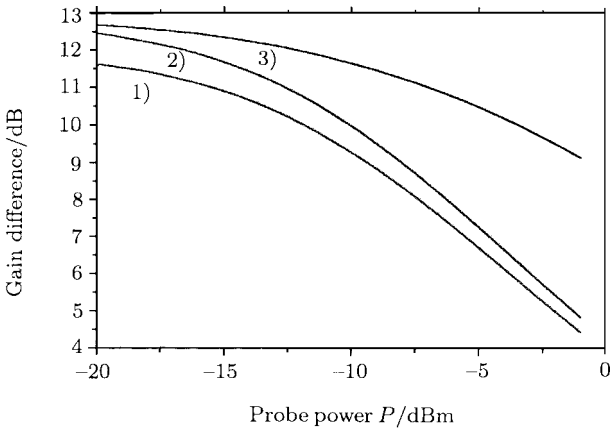


Fig.4. Comparison of the gain difference versus the probe power for three different schemes: 1) 500 μm long, double-port-coupled SOA; 2) 1000 μm long, double-port-coupled SOA; 3) 500 μm long, single-port-coupled SOA. The averaged pump power is 0 dBm.

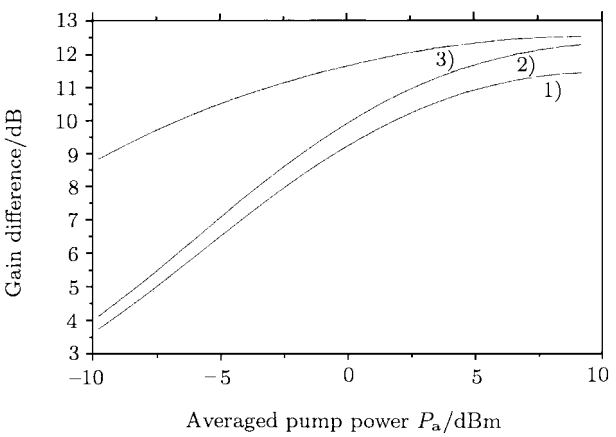


Fig.5. Comparison of the gain difference versus the averaged pump power for three different schemes: 1) 500 μm long, double-port-coupled SOA; 2) 1000 μm long, double-port-coupled SOA; 3) 500 μm long, single-port-coupled SOA. The probe power is −10 dBm.

On the other hand, from Figs.4 and 5, it can be shown that the variation range of the output extinction ratio in the novel scheme is about 3.5 dB for probe power and averaged pump power variations of 20 dB, whereas variation ranges of 7.5–8.0 dB would be achieved in the other two schemes. As the bit error rate is mainly determined by the output extinction ratio, we can conclude that the input dynamic range in the novel scheme is the largest among the three schemes.

IV. CONCLUSION

A novel scheme for XGM wavelength conversion based on a single-port-coupled SOA, in which the input and the output share one port, has been demonstrated with the output extinction ratio as high as 15 dB, even in the wavelength up conversion with a 12.8 nm span. Compared with the conventional schemes based on double-port-coupled SOA, whether with the identical length of the active region or the double length of the active region, the novel scheme can be achieved with simpler implementation, higher output extinction ratio and larger input dynamic range.

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